PM^2 INDUSTRY

VISION AND TECHNOLOGY ROADMAP

POWDER METALLURGY AND PARTICULATE MATERIALS

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METAL POWDER INDUSTRIES FEDERATION
Advancing Powder Metallurgy & Particulate Materials Worldwide

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OFFICE OF INDUSTRIAL TECHNOLOGIES

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Executive Summary

Commercial powder metallurgy, a process for forming metal parts by heating compacted metal powders to just below their melting points, has existed for about 100 years. However, only in the last 20 years has powder metallurgy become widely recognized as a superior way of producing high-quality components for a variety of important applications. The PM^2 industry fabricates semi-dense and fully dense products using several different technologies, including pressing and sintering, injection molding, hot isostatic pressing, and forging. The end application dictates the properties required, and thus the processing route used. Producing near-net shape components with tight dimensional tolerances at modest temperatures provides powder metallurgy with a distinct advantage over other metal forming techniques such as forging and metal casting. Powder metallurgy minimizes finishing operations and energy use while adding design flexibility and lowering costs to end-use customers. These advantages have enabled the PM^2 industry to grow at an average rate of almost 11 percent per year over the past eight years and capture impressive shares of key markets such as the automotive market.

By all accounts, the PM^2 industry has been a model of success over the past decade. PM^2 shipments have more than doubled since 1990, and North American sales of ferrous powder materials, tooling and process equipment, and finished components reached an estimated $7.0 billion in 2000. Longer production runs and cost reduction programs have made the North American PM^2 industry the most competitive in the world; U.S. producers now control over half of the global market for PM^2 parts.

Despite these successes, the PM^2 industry has reached an important juncture in its evolution. While the near-term outlook for the industry appears healthy, continued success will require new innovations, continued improvements to quality and costs, and a visionary view of how the industry will evolve and prosper in an increasingly competitive global environment. Much of the industry's market growth has come at the expense of competing metal forming industries, which are working vigorously to recapture lost market share by developing new process technologies. More importantly, new opportunities are emerging to use a variety of particulate materials in conjunction with metal powders to produce complex components with special properties for an assortment of high-value applications in medicine, electronics, and consumer products. Increased competition and new opportunities are expected to reshape the industry in a profound way. PM^2 component manufacturers must pursue product innovation through process innovation, becoming more agile without sacrificing quality or raising costs to stay competitive.

Definitions

P/M
This is the abbreviation that refers to the powder metallurgy process used to create semi- and fully dense components from metal powders.

PM^2
This term refers to "Powder Metallurgy and Particulate Materials", denoting the use of the P/M process with both metal and non-metal particulate materials. PM^2 is used to refer to the industry which uses these materials to create components.

In order to respond to these new trends, the PM^2 industry, under the coordination of the Metal Powder Industries Federation (MPIF), has charted a bold, new course. Inherent in this effort is the desire to provide high-quality components and services that add value to customer products and operations. This vision and technology roadmap is the result of a year-long cooperative process and outlines a technology strategy to ensure industry growth in current and new markets while improving productivity, quality, efficiency, and environmental performance. The vision lays out the industry's view of future customer and market expectations and the goals designed to meet these expectations. The technology chapters provide a detailed research agenda that can guide R&D investments for the benefit of the entire PM^2 industry.

The PM^2 industry's vision is bold: to become the preferred source of net-shaped metal-based systems by combining unmatched engineering and manufacturing capabilities to bring the highest-value components to a diverse customer base. The vision is supported by a set of market and technical goals (summarized on page 15) that are designed to address the key parameters in achieving the vision: market growth and diversification, productivity improvements, time compression, quality enhancements, human resources, and energy efficiency.

The vision and goals are not easily achieved. A comprehensive technology strategy is needed to ensure the limited R&D resources are used in the most effective manner to achieve the goals and realize the vision. The strategy the PM^2 industry will use as its guide over the next 20 years has three main thrusts:

- **Enhanced Material Properties and Performance —** The industry will pursue revolutionary advances in material science and powder processing, leading to new capabilities that will harness the full potential of making metal-based components from powders.
- **Improved Manufacturing and Processing —** Improving processing and manufacturing capabilities and expanding the range of component size and complexity PM^2 companies can produce will allow them to offer a wider variety of components at competitive costs.
- **Enabling Technologies and Infrastructure —** Technical advances in areas such as sensors, process controls, information technology, diagnostics, and modeling will be incorporated into PM^2 processes to make advances in materials and processes as widely applicable and cost- and energy-efficient as possible.

Within each research thrust R&D priorities are organized into several categories. The figure on the opposite page shows how these research thrusts and priorities are aligned to achieve the goals and vision by addressing critical technical challenges. The detailed research needs for each thrust can be found in Chapters 5, 6, and 7 respectively. Chapter 8 presents a more detailed description of the most critical research needs and presents a plan for their successful implementation. A coordinated research collaboration that combines the talents and resources of individual PM^2 companies, private research organizations, universities, and the government will facilitate a balanced, organized approach to conducting the R&D outlined in this roadmap.

When considering the broad range of research needed to address the industry's technical challenges and realize their goals, six themes emerge that respond to the complex trends and technical issues of the next 20 years:

➤ **Increase material options**. Customer demand for low-cost, high-performance components and systems will drive companies to improve the range and functionality of PM^2 components by applying traditional processing techniques to new materials. PM^2

Overview of PM² Industry Vision and Technology Roadmap

Vision

THE PM² INDUSTRY WILL BE THE PREFERRED SOURCE OF NET-SHAPED METAL-BASED SYSTEMS

Market and Technical Goals

Market Goals → Technical Goals

✓GOAL: Automotive
Increase automotive market by 12% per year through 2020

✓GOAL: Non-Automotive
Increase non-automotive markets by 25% per year through 2020

✓GOAL: Productivity
Enhance productivity by 5% each year through 2010 and 8% by 2020

✓GOAL: Quality
Achieve six-sigma quality for all components by 2005; achieve AGMA 9 by 2005 and AGMA 10 by 2020 at six sigma

✓GOAL: Energy & Environment
Reduce overall energy consumption by 50% by 2010 and 80% by 2020

✓GOAL: Time Compression
Reduce total time to market from two years to six months by 2010 and one month by 2020

✓GOAL: Human Resources
Increase university and technical school graduates entering the PM² industry by 500% by 2010

Key Challenges

Materials Challenges
- Insufficient knowledge of porosity-property relationships
- Shortage of thermophysical data for new materials

Processing Challenges
- Inability to compact to 100% density with dimensional accuracy at low cost
- Lack of 3D forming processes for large components

Cross-Cutting Challenges
- Lack of process models and in situ sensors for materials and process controls
- Shortage of non-intrusive sensor materials

Research Thrusts and Priorities

Materials

Powder Processing
Explore fine particle and nanocrystalline powders

Material Science
Improve understanding of powder microstructure-performance relationships

New Materials
Explore new materials to better understand properties, processes, and potential applications (fine structured, amorphous, etc.)

Composite Materials
Study method of cosintering composites with different materials

Processing

Strengthening and Finishing
Develop new energy efficient sintering techniques

Manufacturing Science
Minimize process interruptions to move to more continuous production

Forming
Non-traditional processing techniques

Advanced Compaction
Methods to achieve full density with tight dimensional tolerance cost effectively

3-D Forming
Rapidly form complex 3-D components (selective laser sintering, rapid prototyping)

Rapid Manufacturing
Systems for more rapid manufacture of products

Equipment and Tooling
Increase automation, uptime, and speed

Enabling

Modeling
User-friendly math-based process models

Sensors and Controls
Use new or existing sensor technology in innovative ways

Design Tools
Develop a web-based design advisor

Testing and Demonstration
Establish agile PM² test-bed facility to gather data

Standards
Develop standards closer to actual application

R&D Structure
Form collaborative partnerships with other industries and government

Technology Planning Logic Flow

companies will shift their focus from metal powders exclusively to metal-based particulate material systems, which may incorporate ceramics, polymers, biological materials, and other new materials along with traditional metal powders.

- **Shift to flexible, agile manufacturing.** Rapidly changing market requirements will encourage PM² companies to develop new manufacturing capabilities that quickly deliver superior quality PM² components to customers at reasonable costs. Flexible, agile manufacturing will enable the industry to undertake both limited and high-volume production runs with exceptional efficiency. Streamlined manufacturing capabilities will reduce time to market and increase value to customers.

- **Expand design and processing capabilities.** The ability of the PM² process to produce totally engineered components and place the right material in the right location will become a distinguishing feature of the industry. Enhanced processing capabilities that enable net-shape production, tight dimensional tolerancing, large and small sizes, and compatibility with total systems (e.g., joining, etc.) will provide customers with a wide range of component shapes, sizes, and functionality.

- **Improve supply chain efficiencies.** Integration of the companies and personnel engaged in the design, powder production, tooling, financing, and delivery of PM² components will greatly speed turnaround times, improve quality, and enhance value. Information technology will improve the efficiency of the supply chain and enable designers, tool makers, and parts producers to work seamlessly to develop and deliver quality components at record speed.

- **Focus on emerging product needs.** Trends in automotive, electronics, and other customer markets will dictate material and component choices and redefine PM² opportunities. For example, reliance on the internal combustion engine is decreasing and PM² producers must develop the materials and systems required for emerging fuel cell and hybrid-electric vehicle technology. The combination of advanced engineering capabilities and sophisticated manufacturing capabilities will attract new customers in emerging markets to the advantages of PM² components. The industry will continue to focus on providing customers with the highest-value component or system.

- **Cultivate critical industry resources.** As the industry pursues new opportunities and challenges, it will cultivate the required resources to sustain growth. A skilled work force, new information technology, access to capital resources, alliances with suppliers and customers, and technology innovation are all essential ingredients for successful market growth.

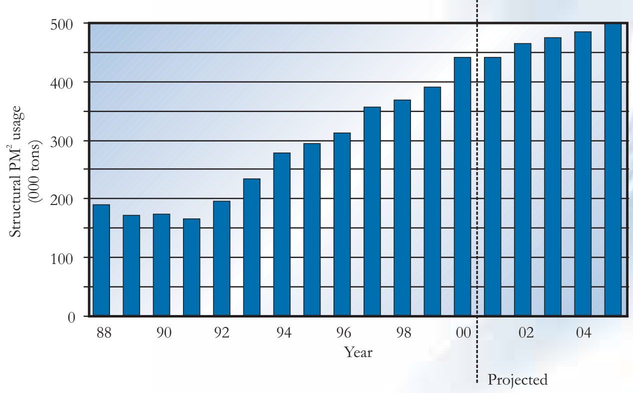
The past growth in PM² shipments has taught the industry that delivering performance and value is the key to market success. However, market requirements frequently change, and continual innovation in technology and business will be required for the future success of the industry. As customer expectations increase and competition intensifies, the PM² industry must capitalize on its advantages as the most cost-effective process for producing net-shape components and the best process for producing complex engineered components and systems. By incorporating new materials and manufacturing processes, the PM² industry can pursue new markets and applications, many of which contain high-value products. *The PM² industry must embrace these opportunities and challenges by uniting behind its vision and technology roadmap to secure existing markets, open new markets, and sustain industry growth.*

1 Overview of the PM² Industry

Uses of PM² Products

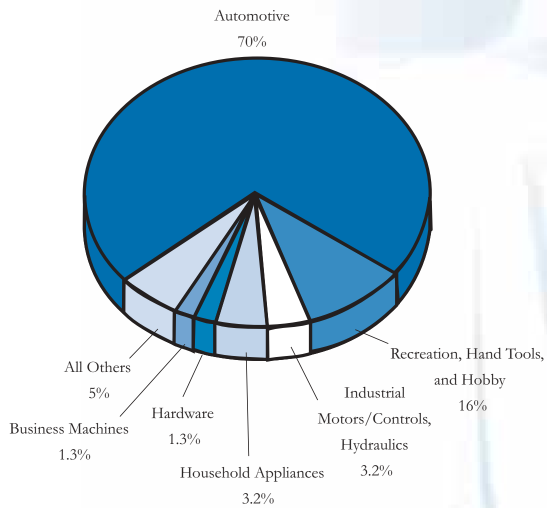
PM² applications fall into two main groups. The first group consists of components difficult to make by any other production method, such as those components made from tungsten, molybdenum, or tungsten carbide. Porous bearings, filters, and many types of hard and soft magnetic components are also produced exclusively by the P/M process. The second group of applications consists of components for which PM² is a cost-effective alternative to machined components, castings, and forgings. Examples are automotive components such as clutch plates, connecting rods, cam shafts, and planetary gear carriers.

PM² Production (Iron and Steel) 1988-2005



PM² components are used in a variety of markets, most notably the metal cutting and automotive industries. Other important markets are recreation and hand tools, household appliances, industrial motors and controls, hardware, and business machines. PM² components are also used in products such as electronics, aircraft turbine engines, riding lawn mowers, surgical instruments, oil/gas well drilling equipment, and off-road tractors. PM² components are used because they offer a combination of superior performance, cost, and tolerances that cannot be matched by other processing means. The industry has enjoyed nine years of consecutive growth from 1991 to 2000 as measured by tons of product shipped. While shipments are expected to be flat in 2001, projections based on current and anticipated market trends indicate growth will be sustained for at least another five to seven years.

PM² Structural Components Markets 2000



The fortunes of the PM² industry are tied directly to those of the automotive industry because that sector consumes 70 percent of all ferrous PM² components produced. The amount of PM² components used in vehicles has more than doubled over the past 20 years, from an average of 16 pounds (7 kg) in 1978 to 36 pounds (16 kg) in 2000, and is expected to continue to rise to 50 pounds (28 kg) in the near future. Meeting automotive needs is critical to the success of the PM² industry and is central to the industry's vision.

Structure of the Industry

The PM² industry is comprised of three major segments:

- powder, lubricant, industrial gas, and raw material producers
- tooling, process equipment, and service suppliers
- contract and in-house component fabricators

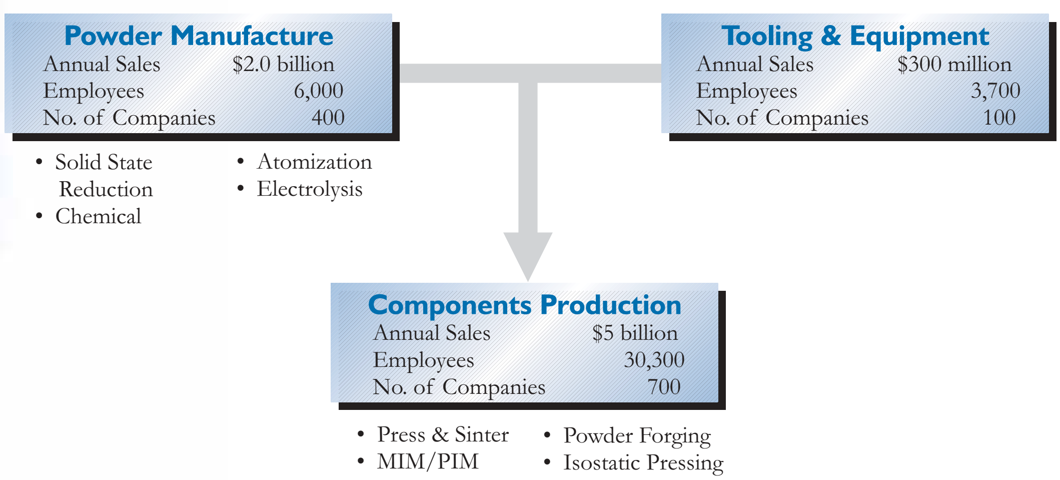
Estimated sales from all three sectors in North America total over $7.0 billion with employment exceeding 40,000 people. The majority of PM^2 companies are small; 90 percent of the firms are classified as small businesses by U.S. government standards. However, roughly half of all employees work for a handful of large companies that dominate the industry in terms of employment.

Powder Producers – In 2000 the value of U.S. metal powder shipments alone was $2.0 billion. Worldwide metal powder production exceeds one million tons annually. North American metal powder shipments remained relatively flat in 2000 at 563,533 short tons (511,229 metric tons), a two percent increased over 1999 shipments. The most common metal powders available are iron and steel, tin, nickel, copper, aluminum, and titanium, as well as refractory materials such as tungsten, molybdenum, and tantalum.

Tooling and Equipment Makers – Approximately 100 tooling and equipment companies serving the PM^2 industry operate in the United States, accounting for $300 million in sales annually. The products of this sector are directly responsible for an estimated 44 percent of the end product's energy consumption. Companies in this sector supply equipment and technology for compaction and/or sintering processes, including presses, dies, and furnaces.

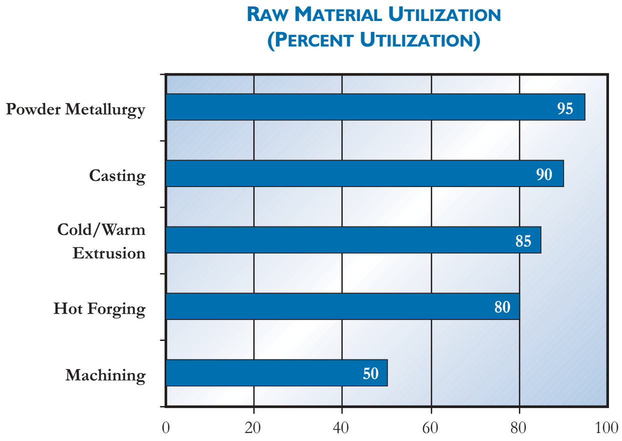
Component and Product Producers – The North American PM^2 industry is as large as the rest of the world industry combined. Component producers are often custom fabricators acting as job shops for OEMs. A few companies have their own captive or in-house suppliers of PM^2 components (e.g., Caterpillar, Black & Decker), and PM^2 component producers serving as stand-alone processing companies are largely a North American trend.

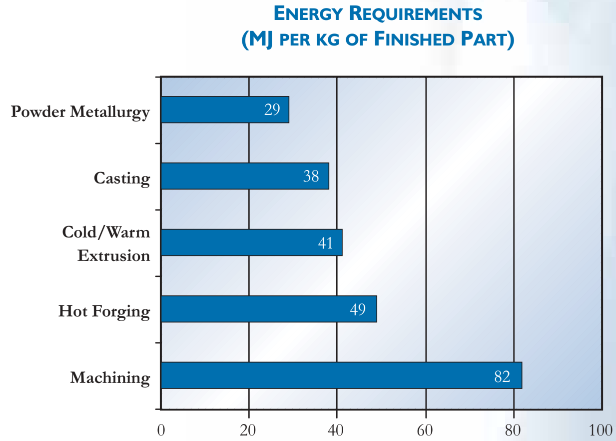
Structure of the PM^2 Industry



Technology Overview

PM^2 gains acceptance among component manufacturers and users when value can be offered by reducing raw material needs and labor requirements through the elimination of extensive machining operations. The basic P/M process is capable of producing simple or complex net or near-net shaped components at production rates that range from a few hundred to several thousand components per hour. PM^2 components also may be sized for closer dimensional control and/or coined for both higher density and strength.





The P/M process begins by mixing elemental or alloy powders with lubricants and then molding the mixture in a die. Afterwards, the shapes are sintered or heated in a controlled-atmosphere furnace to bond the particles metallurgically without melting or only partially melting. The component may undergo a variety of additional manufacturing and finishing steps, such as coining, sizing, forging, rerolling, machining, heat treating, electroplating, and steam treating.

A brief technology overview for each of the three main segments of the PM² industry is presented below.

Powder Manufacture

The first step in the overall P/M process is making metal powders. There are four main processes used in powder production: solid-state reduction, atomization, electrolysis, and chemical.

Solid-State Reduction

In solid-state reduction, selected ore is crushed, mixed with a reducing species (e.g., carbon), and passed through a continuous furnace. In the furnace, a reaction takes place that leaves a cake of sponge metal which is then crushed, separated from all non-metallic material, and sieved to produce powder. Since no refining operation is involved, the purity of the powder is dependent on the purity of the raw materials. The irregular sponge-like particles are soft, readily compressible, and give compacts of good pre-sinter ("green") strength.

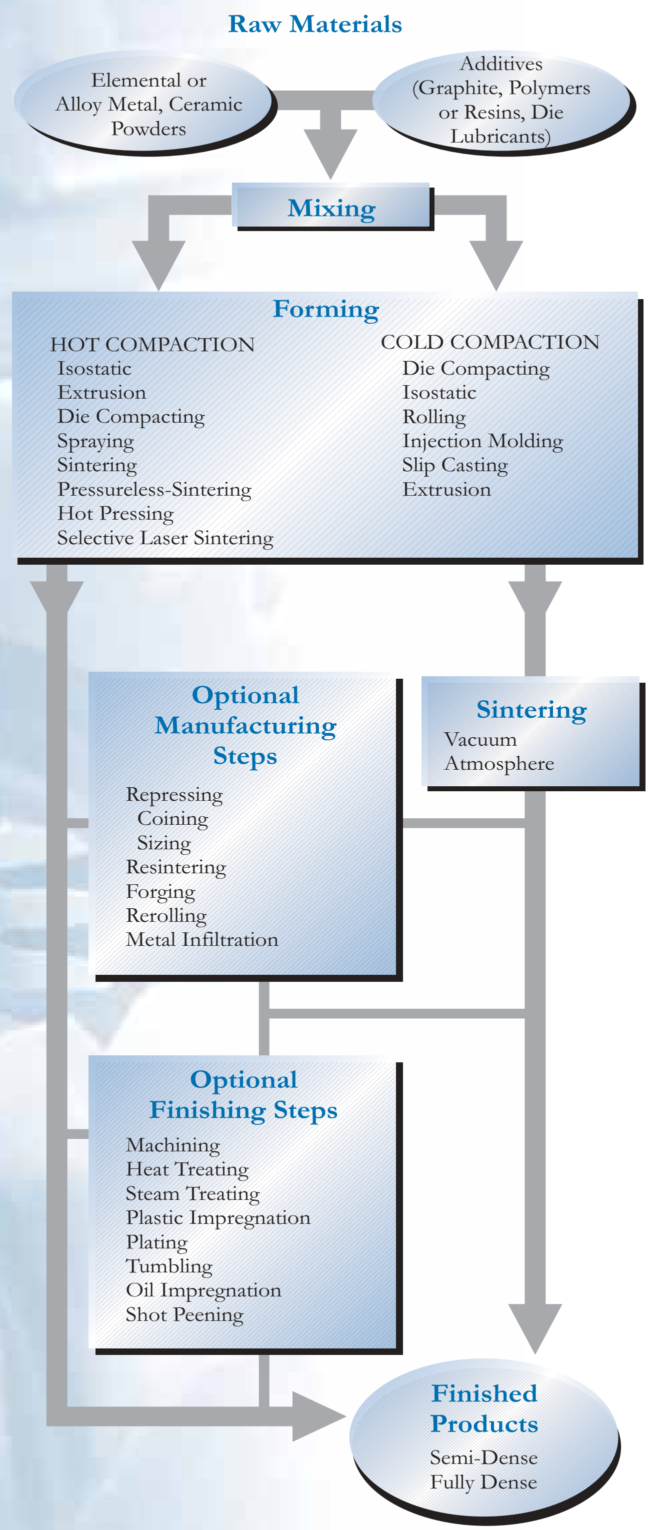
Atomization

In this process, molten metal is separated into small droplets and frozen rapidly before the drops come into contact with each other or with a solid surface. Typically, a thin stream of molten metal is disintegrated by subjecting it to the impact of high-energy jets of gas or liquid. In principle, the technique is applicable to all metals that can be melted and is used commercially for the production of iron, copper, alloy steels, brass, bronze; low-melting-point metals such as aluminum, tin, lead, zinc, and cadmium; and, in selected instances, tungsten, titanium, rhenium, and other high-melting-point materials.

Electrolysis

By choosing suitable conditions, such as electrolyte composition and concentration, temperature, and current density, many metals can be deposited in a spongy or powdery state. Further processing — washing, drying, reducing, annealing, and crushing — is often required. Copper is the primary metal produced by electrolysis but iron, chromium, and magnesium powders are also produced this way. High-purity and high-density powders are two distinguishing features electrolysis offers. Electrolysis is not generally used due to high energy costs associated with the process; use is limited to high-value powders such as high-conductivity copper powders.

The Powder Metallurgy Process



Chemical

The most common chemical powder treatments involve oxide reduction, precipitation from solutions, and thermal decomposition. The powders produced can have a great variation in properties and yet have closely controlled particle size and shape. Oxide-reduced powders are often characterized as "spongy", due to pores present within individual particles. Solution-precipitated powders can provide narrow particle size distributions and high purity. Thermal decomposition is most often used to process carbonyls. These powders, once milled and annealed, exceed 99.5 percent purity.

Tooling And Equipment Design

Tooling and equipment are designed to impart specific geometric characteristics to a component based on a predetermined shape. Tooling allows precise control over the final product shape while attaining rapid production rates of thousands of components per hour. Because of the wide variety of PM² components produced, tooling and equipment are often customized for each desired component.

Component Production

During component production, tooling and equipment, sintering, and finishing operations turn the raw materials (metal powders) into the final component. There are four key processes in component production within the PM² industry: press and sinter, powder-injection molding (PIM), powder forging, and isostatic pressing.

Press And Sinter

The press and sinter approach consists of four main stages: mixing the powders with a lubricant, pressing them together in a die under high pressure, and heating the component that emerges from the die at a temperature below the melting point of the main constituent (sintering), and any additional processing steps such as repressing or plating. Press and sinter is used to create conventional PM² components and products from iron, aluminum, and copper-base powders, specialty PM² products such as superalloys, porous products, friction materials, strip for electronic applications, high-strength permanent magnets, tungsten carbide cutting tools and wear components, and tool steels. Liquid-phase sintering is also used within the PM² industry to produce components from tungsten-carbide, tool steels, and other hard metals. Generally, press and sinter produces semi-dense components.

Powder Injection Molding

Metal injection molding (MIM) and powder injection molding (PIM) have emerged as competitive manufacturing processes for small precision components. These processes eliminate one significant limitation of the P/M process: components with undercuts or multiple projections forming right angles with the pressing direction cannot be made directly. The processes are capable of producing complex shapes from many materials, including metals, ceramics, intermetallic compounds, and composites, in both large and small volumes. New applications for components made from MIM and PIM are developing in the automotive, chemical, aerospace, business equipment, computer hardware, biomedical, and armaments industry sectors. PIM is used to produce components that may or may not be fully dense, depending on their intended application.

Powder Forging

In this process, a powder blank is pressed to a shape halfway between a forging billet and the finished component. This compact, referred to as a preform, is pressed and hot forged to the finished size and shape in a closed die. The amount of deformation involved is sufficient to give a final density close to that of solid metal. Consequently, the mechanical properties of powder forged components are comparable with those of material forged from ingots.

Isostatic Pressing

Isostatic pressing utilizes high pressures (around 65,000 psi/450 MPa) to uniformly compress a component to full density. This technique can be performed at high or ambient temperatures, although hot isostatic pressing (HIP) eliminates the need for subsequent sintering. Isostatic pressing and HIP produce fully dense components.

2 Key Trends and Drivers

Over the next 20 years, the PM² industry will confront serious challenges and exciting, new opportunities. Environmental concerns will significantly alter the focus of the metal cutting and automotive sectors, the industry's biggest customers. The Internet will continue to revolutionize the business world. External factors such as accelerated globalization and an aging U.S. population will create both potential markets and barriers for the industry. The PM² industry's ability to respond to these and other factors while providing new and existing customers with innovative, cost-effective solutions will be the key to sustaining the growth it has enjoyed over the past decade.

Most Critical Trends and Drivers

- Decreased auto industry dependence on internal combustion engine
- Growing customer demand for high-performance materials
- Shift in net-shaping to less reliance on machining and sintered cutting inserts
- Increasing need for more precise net-shaped manufactured products
- Move to agile manufacturing while reducing downtime and achieving six-sigma quality
- Increasing supply chain integration through total process modeling and e-business
- Limited supply of skilled workers and limited resource base to attract new workers

Markets And Customer Demands

Customers create the forces that drive the PM² industry. The industry must respond to the changing needs and demands of existing and potential customers with agility and ingenuity while maintaining higher value than competing materials technologies.

Automotive Trends

Automotive industry decreases dependence on the internal combustion engine. Efforts to improve fuel efficiency in vehicles are favoring fuel cells and hybrid-electric vehicles. Because the automotive industry represents 70 percent of all ferrous PM² sales, any sweeping change in that sector presents the PM² industry with serious challenges. The PM² industry has a tremendous opportunity to provide components for these new vehicle propulsion systems. In the near term, however, this shift away from internal combustion engines may reduce the demand for PM² components.

Consolidation within the auto industry continues. As first- and second-tier suppliers respond to cost pressures, PM² companies must stay abreast of structural changes and respond accordingly to ensure their place within the automotive supply chain. The automotive industry will continue to increase its outsourcing of components and technical expertise, creating more opportunities for PM² companies to provide automotive customers with products and services. However, as automotive companies expand to developing markets, PM² companies will also face increased competition from both domestic and foreign component manufacturers often utilizing competing technologies.

Materials Trends

Customers demand improved performance from components. PM² customers will demand improved performance and value from their components through lighter weights, higher strengths, better magnetic properties, improved chemical homogeneity, improved wear resistance, and higher operating temperatures. To meet these demands, PM² companies will be required to develop high-performance material systems, incorporating multiple materials to improve material efficiency (functional gradients, layered structures, etc.), porous materials, and unusual alloys with unique microstructures while continuing to provide the best value on the market.

Material standards become more critical, particularly on a global scale. The development and implementation of material standards on an industry-specific, national, or global scale will strongly influence the future PM^2 industry by creating more rigid specifications to which PM^2 materials and components must adhere.

New Markets

Market opportunities emerge in existing and new disciplines. New developments over the next 20 years will open tremendous opportunities for the PM^2 industry to enter new, thriving markets. The growing telecommunications, electronics, cutting tools, leisure sports, biotechnology, home/office automation, mass transportation, and other high-tech industries will need component solutions as they provide new products and services to an eager consumer base.

Production Trends

As the technical requirements of PM^2 customers grow, the industry must modify the way it creates powder, equipment, and components. PM^2 industry operations must deliver increased value by improving technology at similar or lower cost.

Supply Chain

Supply chain management and integration improves with information technology. Time to market is a critical factor in determining the value a particular component can offer. Information technology tools, such as total process modeling and e-business, will advance at a rapid speed, offering the industry new capabilities and potential to integrate powder, tooling, and component suppliers with customers.

Manufacturing Environment

Agile manufacturing permeates the industry. Manufacturing agility will ensure PM^2 companies are positioned to quickly respond to changes in customer demand and continue to supply the highest-value components at shorter times to market. Such agility and flexibility is particularly critical in a increasingly capital-intensive industry such as PM^2 — large capital investments have long lifetimes and must remain productive over their duration. Knowledge management systems, virtual manufacturing, and increased automation will enable agility and flexibility in manufacturing, reducing time to market and thus further increasing the value of PM^2 components. Flexibility, when combined with rapid prototyping and other advances, will allow PM^2 companies to offer mass customization to customers, thereby combining the value of large manufacturing operations with the ability to offer customized components and short production runs.

Industry increases emphasis on quality. Customers will soon demand six-sigma quality in many applications; new manufacturing systems must achieve this level of quality. Six-sigma quality must be achieved while also increasing tolerances to new levels of precision. Part diagnostics such as non-destructive evaluation (NDE) and green crack detection techniques will become increasingly pervasive throughout the industry. Significant capital investment will be necessary as manufacturing operations are adjusted to reach new tolerance and quality levels while maintaining cost-effectiveness.

Processing Trends

Customer demand for advanced component properties increases. As PM^2 customers strive to offer new products to consumers, they will require components or systems that cannot be produced economically by today's PM^2 industry. Examples include highly complex geometries, large or small components, 3-D component manufacturing, and better compatibility or joining ability with other materials. In addition, more precise dimensional tolerancing to meet tight component specifications will grow in importance.

PM^2 processes improve by incorporating cutting-edge technology. Novel and hybrid processes such as thixotropic forming, spray forming, surface engineering and conditioning, and adherent-clad layering will offer PM^2 companies more processing options. Real-time feedback control at each step in the PM^2 process will help control processing quality and speed. The ability to tailor shapes and properties will better position PM^2 companies to meet specific customer demands.

Industry Infrastructure

As the PM^2 industry responds to customer demands and improves its performance, the structure of the industry will undergo changes typical of a growing, maturing industry.

Industry Structure

Consolidation dominates overall industry structure. As the PM^2 industry matures, companies will continue to join, combining resources and customer bases and creating the potential for several global companies to dominate the marketplace. Smaller entrepreneurial companies will continue to thrive as they serve specific niche markets, but their collective market share will shrink in relation to that of large PM^2 companies and vertically-integrated megacompanies. These integrated companies will have more R&D resources and sophistication at their disposal, helping to further advance component capabilities.

Economics and Finance

Attracting investors to capital-intensive industries is difficult. Manufacturing industries have experienced the difficulty of attracting investors to generate the capital required to install new capacity because return on investment is typically lower or more long-term. Although this trend may be reversing, the PM^2 industry is an increasingly capital-intensive manufacturing industry and may experience difficulty in realizing its full growth potential because of capital limitations. The PM^2 industry, as an increasingly capital-intensive manufacturing industry, is no different and may experience difficulty in realizing its full growth potential due to this lack of capital.

Limited R&D resources exist for all PM^2 companies, particularly smaller ones. Because the generally low return on investment due to aggressive pricing in the PM^2 industry, many companies lack the resources to aggressively pursue R&D, particularly projects with higher risk or longer time frames. Limitations are particularly severe for smaller companies which have even tighter resource constraints. As consolidation continues within the industry, the larger companies which emerge will face less severe resource constraints.

Human Resources

Supply of skilled workers continues to be limited. The supply of skilled workers, both technical staff (engineers) and semi-skilled laborers, is limited throughout the industry. PM^2

companies have a limited resource base to attract new engineers to the industry because of severe pressures to maintain cost-effectiveness, thus constraining wages they can offer skilled new engineers and scientists. Compounding this shortage is an increasing retirement rate of existing employees, diminishing the expertise resident within the industry. Tools such as on-job training programs and knowledge repositories will play a vital role in alleviating this trend.

Global Factors

Many broad, societal factors, external to the industry, will also influence the PM² industry. The North American PM² industry, like other manufacturing industries, will be forced to embrace these external factors to continue to flourish.

Globalization

Globalization continues to impact business. PM² companies will grow to international scales as the global economy grows and developing nations emerge as key markets. As some nations emerge as key PM² markets, particularly in Asia and South America, many companies may consider international locations or partnerships. At the same time, the Internet and other communications technologies will render geography less important in the global business world, forcing companies to carefully evaluate their business strategy in global markets.

Energy and Environment

Society and government continue to demand environmental responsibility. Safety, health, and environmental regulations (particularly air quality regulations) are likely to increase both in magnitude and number. Alternative energy sources will be aggressively explored and developed as fossil fuel supplies are depleted. These factors will create pressures on the PM² industry to reduce energy usage throughout its operations, and increase its focus on the recyclability of components and systems.

PM² components favored because of their energy-efficiency benefits. Customers will look for the most environmentally responsible components on the market in an effort to respond to public and government demand for enhanced environmental performance. Because the PM² process is more energy- and material-efficient than competing technologies such as forging and casting, PM² companies will have tremendous opportunities to enter new markets.

Megatrends

Changes in transportation affect the PM² industry. As society becomes less energy- and material-intensive, transportation technology is likely to undergo substantial changes. Mass transportation may overtake personal vehicles as the preferred method of transportation. Virtual technology may greatly reduce the need or demand for transportation. In the more immediate future, automotive manufacturers are increasingly considering light weight as one of the key factors for material selection as a method for improving fuel economy. These trends have the potential to severely alter the automotive industry, and thus the PM² market.

An aging population shifts consumer demands. The demand for health care products and systems will increase, causing that market to seek new solutions for which PM² may be suited. Additionally, lifestyle shifts will increase the demand for leisure activities and goods, already a key market for the PM² industry. Demand for electronics and telecommunications technologies will also rise, creating enormous market potential for PM² components in those applications.

3 Vision and Market Goals

The PM² industry is entering a time of serious challenge and tremendous opportunity. Change within the automotive industry, stiffer competition from other metal-forming processes, increasing customer expectations for high-performance materials and systems, and the constant need to improve cost-effectiveness of components are all shaping business strategies throughout the industry. PM² companies realize that to effectively compete in this new business environment, they must plan now for success in the future.

Vision

By 2020, the PM² industry will be the preferred source of metal-based, net- shaped components and systems. The industry will supply the highest-value solution for a wide range of applications by combining engineering ingenuity with flexible manufacturing and a seamlessly integrated supply chain. Enabled by twenty years of strategic technology development, environmentally responsible PM² components of the highest quality will be delivered to a diverse customer base at increasing speed. These advances will allow the PM² industry to sustain growth rates that exceed national economic growth.

By 2020, the PM² industry will be the preferred source of net-shaped metal-based systems. Unmatched engineering and manufacturing capabilities will allow PM² companies to offer the highest-value components to a diverse customer base.

Infinite Material Options

As customers continue to raise the performance level of their products, PM² companies will use novel particulate manufacturing to supply the components they require. These companies will combine the benefits of traditional metal PM² components with the advantages of other material classes, such as ceramics, advanced powders, polymers, and biomaterials, to create a new generation of PM² components that provide advantages such as higher strength, lighter weight, and better system compatibility than traditional metal-only components. Because competing metal forming industries lack the ability to combine materials in components as cost-effectively as the P/M process allows, the PM² industry stands alone in offering an almost infinite spectrum of solutions for both traditional and novel applications.

Totally Customized Components

Combining metals with other material classes in a component is only the first step in satisfying customer needs. In 2020, the industry will have the technical capabilities to allow customers to specify through computer modeling technologies the exact composition of individual metal-based components to better meet technical requirements. Designers will specify precise material locations, creating functionally gradient materials, layered materials, hybrid compositions, and virtually any other configuration that will provide value in the final product. This engineering flexibility will allow PM² components to offer performance, customization, and value that cannot be realized via any other process.

Totally Engineered Systems

The ability to design metal-based material systems is a key strategic advantage for the PM² industry. However, material selection and configuration are not the only elements of a totally engineered system. Advanced production capabilities are essential to cost-effectively produce an engineered component. The industry will deliver components that are net shaped, fully dense, and highly complex in a wide variety of sizes. Coupling materials and component design with advanced production capability will allow PM^2 companies to offer the most options and best time and dollar value to customers.

Agile, Flexible Manufacturing

Once the material is designed and production capabilities are in place, a component must be manufactured quickly, economically, and accurately to maintain its cost-effectiveness. Manufacturing flexibility will allow mass customization, providing the economic and time-to-market benefits of full-scale manufacturing while offering limited production runs of specialty components. Agility and flexibility will also ensure that PM^2 companies can quickly respond to changing market conditions and customer demands, securing their place as a key components supplier in the marketplace.

Seamlessly Integrated Supply Chain

In 2020, companies along the PM^2 supply chain will work together to ensure the highest value component is provided to the customer in as little time as possible, using collaborative engineering to develop technology solutions and reduce the total time required to go from concept to final component. PM^2 companies will be integrated with other parts of the supply chain through information technology, total process modeling, and e-business. When a customer specifies a needed component, those specifications will be instantly communicated to the powder makers, tooling and equipment suppliers, and component fabricators.

Outstanding Value to Customers

Despite competition from other metal forming industries, PM^2 companies will offer significantly more cost-effective solutions to engineering challenges because of their infinite range of materials and component configurations, manufacturing sophistication, and supply chain integration. The industry will strive to provide its customers with the highest-value solutions to almost any engineering challenge. As technology improves throughout the PM^2 process, powder production, tool and equipment design, and component fabrication will all operate at improved efficiency.

Significant Market Growth

Because of its outstanding value, the PM^2 industry will sustain its history of outpacing national economic growth and continue to serve current customers while seeking out new ones. As the automotive industry continues to pursue fuel cells and other alternative vehicle platforms, the PM^2 industry will be positioned to supply the new components they will require. At the same time, the exceptional performance and value offered by PM^2 components will facilitate further entry into telecommunications, home/office automation, biotechnology, health care, and other existing and new markets.

Market Goals

The vision of the PM^2 industry is organized around one key mission: increasing PM^2 markets. For PM^2 markets to grow at aggressive rates, current markets such as automotive, industrial components, and household appliances must continue to grow while new, promising markets including biomedical applications, electronics, and business machines are further penetrated. Some evidence suggests growth in the automotive market will begin to slow, making market diversification an urgent priority for the industry. Armed with a portfolio of new, advanced components created using innovative materials and enhanced processes, PM² companies can better serve existing customers by offering more solutions to technical needs. PM² companies will also have the capabilities they need to venture into new markets which may not be familiar with the value of PM².

The PM² industry has established two goals for market growth over the next twenty years. These goals will help to define the magnitude of the R&D effort needed by quantifying the growth sought, and also help to measure market diversification by tracking both automotive and non-automotive sales.

✓GOAL **Achieve 12% annual market growth in automotive market through 2020.**

✓GOAL **Achieve 25% annual market growth in non-automotive markets through 2020.**

These goals are for non-recession years and measured in constant dollars. Growing current markets while entering new ones will ensure the PM² industry exceeds the success of the past decade. Chapter 4 presents several technical goals that have been established to position the industry to achieve these market goals, as well as the technology strategy formulated to attain the goals.

Selected Market Sector Briefs

Transportation: Technical and Performance Breakthroughs

Historically, the transportation market has been the most technically demanding market served by the PM^2 industry, whether it is the automotive or aircraft segment. The value and opportunity for PM^2 is derived from the need for performance and reliability. The auto segment offers volume to provide the cost support necessary to achieve technical breakthroughs. The aircraft segment offers the high value of each component (wherein many cases, cost is less a concern than reliability and performance) to justify the development of new technologies to realize performance breakthroughs. Material system selection and improved consolidation techniques have enabled those breakthroughs. The industry expects that this market sector will continue to offer similar opportunities.

Medical/Biotechnology: Mimicking Natural Growth Processes

The ability to cost effectively provide complex net-shape design options without extensive machining requirements will continue to attract designers in this sector to PM^2. In addition to the shape of the components, the unique flexibility inherent in PM^2 to provide complex, definable material structure and particle morphology will be viewed as a unique advantage of the technology. PM^2's particulate, "building block", consolidation capabilities that do not require the damaging effects of melting and solidification will offer this segment the opportunity to develop fabrication techniques that will most closely mimic natural processes of growth and formation of structures. The material selection options for strength and biocompatibility will offer unparalleled future opportunity for technical success.

Electrical/Motors: Magnetic Materials and Micromotors

The continued development of insulated powders for hard and soft magnetic applications will fundamentally change the opportunities for the design of motors. Designers will no longer be constrained to use stacks of laminations to build motors. The flexible shapes that can be pressed or molded into stators and armatures using PM^2 consolidation techniques and powders without a loss in electrical performance characteristics will revolutionize this sector. In addition, advanced consolidation capabilities will enable production of "micro" motors using new materials. With the advent of hybrid propulsion systems for transportation, the design and weight advantages of PM^2 will presage a major market opportunity for the technology.

Cutting Tools: Cost Reductions Via Nanoparticles

PM^2 technology has enabled the significant advances achieved to date in cutting and forming tools used in all metal removal processes. The use of new "harder" and tougher materials will continue to permit advances in machining and forming. These advances will be enabled by using nanoparticles of various materials and existing metals and ceramics to achieve breakthrough performance. The value of this technology cannot be underestimated in its importance to continued metal processing productivity and cost reductions.

4 Technology Goals and Strategy

The PM² industry vision describes an industry capable of quickly supplying the highest-quality components to a diverse customer base using advanced materials and processing capabilities to create superior value. This vision will not be reached without significant investments in technology development. However, as with most industries today, resources for research and development are limited. Accordingly, a strategic approach to technology investment is needed to ensure those investments are focused on the most critical needs of the industry.

Technology Goals

To help focus R&D investments, the PM² industry has established five technical goals which support the goals for market growth described in Chapter 3. These goals provide focus on critical characteristics of the PM² vision — efficient processing, quick time to market, superior quality and precision, skilled human resources, and environmental performance, all of which combine to improve the value of PM² components. The goals provide a powerful indication of where the industry will direct its research efforts over the next 20 years. The industry has also established several objectives to support each goal. While the goals are far-reaching, the objectives give indication of specific areas where R&D is needed over the course of the next two to 20 years.

PM² Industry Strategic Goals

- **Markets and Customers**: Achieve 12% annual market growth for automotive markets and 25% for non-automotive markets through 2020.
- **Productivity:** Enhance productivity by 5% every year through 2010, and 8% through 2020.
- **Time Compression:** Reduce total time to market from two years to six months by 2010, and one month by 2020.
- **Quality:** Achieve six-sigma quality for all components by 2005; achieve AGMA 9 by 2005 and AGMA 10 by 2020 (at six sigma).
- **Human Resources:** Increase university and technical school graduates entering PM² industry by 500% by 2020.
- **Energy and Environment:** Reduce overall energy consumption by 50% by 2010 and 80% by 2020.

Productivity

Continuing to provide the best value to customers is the key to successful market growth. Improvements in productivity have a strong impact on the value PM² companies can offer. Improving equipment life will help alleviate the pressures that a capital-intensive industry such as PM² confronts in growing at aggressive rates. Integrating the industry through e-business will improve overall industrial productivity by ensuring that all members of the supply chain are operating in concert.

✓GOAL **Enhance productivity by 5% per year through 2010 and 8% through 2020.**

OBJECTIVES

- Increase sales per employee
- Increase run time of capital equipment; increase tool life
- Fully integrate the industry through e-business

Time Compression

Time to market is critical to profitability for many PM² customers. Decreasing their time to market will help ensure PM² companies continue to provide the highest-value solution for its customers. The industry will focus on both reducing time requirements for individual steps along the supply chain and the total time requirements from component design to steady-state production ("art to part"). Rapid tool manufacturing offers particular promise in overall time reduction.

✓**GOAL** **Reduce total time to market from two years to six months by 2010 and one month by 2020.**

OBJECTIVES

- Reduce cycle time (component print to tooling)
- Reduce tool manufacture time for uniaxial pressing using rapid tooling and fabrication techniques

Quality and Precision

If PM² companies cannot satisfy customers' quality requirements while maintaining cost-effectiveness, customers will turn to other component fabricators. Within 5 years, those requirements will include six-sigma quality for most applications. Demands for tighter tolerances are increasing. European standards use the American Gear Manufacturers Association (AGMA) standards for measuring tolerances; using that standard or a similar scale to gauge progress for the PM² industry will ensure its tolerancing capabilities keep pace with customers' demands. Reducing powder and process variability will make a significant impact on quality throughout the PM² industry in almost every application since variability is a key detriment to quality.

✓**GOAL** **Achieve six-sigma quality for all components by 2005.**

✓**GOAL** **Achieve AGMA 9 by 2005 and AGMA 10 by 2020 (at six sigma).**

OBJECTIVES

- Reduce powder variability
- Move from adaptive process control to closed-loop feedback process control

Human Resources

Industry growth of the magnitude described in the market goals cannot be achieved without fueling the industry with the needed human resources. Recruiting new people while the existing workforce ages is a difficulty the PM² industry shares with other manufacturing industries. Further, the remote locations where the PM² industry is concentrated are not attractive to many young people. Expanding educational efforts to create a supply of qualified employees and developing technical centers to maintain knowledge otherwise lost to retirement will be critical in solving the personnel shortage across the industry. In turn, industry recruiting efforts must expand in proportion to increased output, and rewards must be competitive with other industries.

✓**GOAL** **Increase number of university and technical school graduates entering the PM² industry by 500% by 2020.**

OBJECTIVES

- Develop additional university technical centers or expand existing ones
- Match industry human resource needs with university output

Energy and Environment

PM² energy and material requirements are lower than competing processes such as forging and casting, giving the industry a competitive advantage. However, competing processes are aggressively pursuing technologies that will increase their energy and material efficiencies. Improving energy and material requirements not only fortifies a key PM² advantage, but also protects the environment. Reducing emissions improves worker safety by removing all harmful emissions. Efficiency gains are needed in all stages of the PM² process, including powder manufacturing, sintering, and secondary component producing processes. Recycling PM² components will also be improved to minimize waste.

✓**GOAL** **Reduce overall energy consumption by 50% by 2010 and 80% by 2020.**

OBJECTIVES

- Reduce energy consumption in sintering and powder making; reduce process atmosphere consumption
- Reduce all emissions and waste products; reduce scrap/rework in component fabrication
- Increase recycling of PM² materials; consider recycling and reclamation of products during materials development

Technology Strategy

For a technology-driven industry such as the PM² industry, technology development is a critical part of achieving the goals and vision. However, for many reasons including demands for near-term profits, many individual companies have somewhat limited resources devoted to technology development, particularly long-term, high-risk technologies. A comprehensive yet strategic approach to technology development will help ensure those limited resources are leveraged and applied along critical technology paths to create maximum impact throughout the industry. Successful research programs will ensure those investments position the industry for competitive success through the next 20 years.

The strategy that will drive PM² technology development has three main components:

➤ **Enhanced Material Properties and Performance —** Customers turn to PM² components because they offer superior value. This value is in part achieved by providing material properties and performance that other material systems can't match at similar costs, and in some cases providing components made from materials only PM² can offer due to their unique nature (e.g., tungsten filaments). In order to hone this competitive edge, the industry will pursue revolutionary advances in material science and powder processing, leading to new capabilities that will harness the full potential of making metal-based components from powders. *Research to improve material capabilities is primarily directed at achieving the goals for market growth described in the previous chapter.*

➤ **Improved Manufacturing and Processing —** The other key component of PM²'s superior value, as well as the true core and identity of the industry, is the P/M process used to create structural metal components. Improving this process and expanding the range of component size and complexity will allow PM² companies to offer a wider variety of components at competitive costs. Additionally, improving asset utilization will allow PM² companies to continue supplying their customers with the highest-value products by improving their quality and speed with which those products are delivered. *Research to improve manufacturing and processing capabilities is primarily directed at achieving the technical goals for productivity, quality and precision, and energy and environment.*

➤ **Enabling Technologies and Infrastructure —** It is essential that enabling technologies are developed to make advances in materials and processes widely applicable and as cost- and energy-efficient as possible. Technical advances in areas such as sensors, process controls, information technology, diagnostics, and modeling will be incorporated into PM² processes to achieve the industry's productivity, quality, time to market, and energy-efficiency goals. In addition, coordinated research collaboration that combines the talents and resources of individual PM² companies, private research organizations, universities, and the government will facilitate a balanced, organized approach to conducting the R&D outlined in this roadmap. Such collaboration will also help to secure a steady stream of human expertise available to the industry by further engaging the academic community in the industry. *Research to develop enabling technologies is primarily directed at achieving the technical goals for time compression and human resources.*

The diagram on the opposite page shows how the three research thrusts align with the strategic goals and key challenges, as well as some of the highest-priority technical needs. The research areas are discussed in detail in the three subsequent chapters, including presentation of the entire range of near-, mid-, and long-term R&D needs. It is essential that these research components are all pursued in concert using an organized approach. Only by broadening material options, improving manufacturing efficiencies, and incorporating the necessary enabling technologies through broad research collaboration will the PM² industry be positioned to expand and diversify its markets and prepare for the challenges of the next 20 years.

Overview of PM² Industry Vision and Technology Roadmap

Vision

THE PM² INDUSTRY WILL BE THE PREFERRED SOURCE OF NET-SHAPED METAL-BASED SYSTEMS

Market and Technical Goals

Market Goals → Technical Goals

✓GOAL: Automotive
Increase automotive market by 12% per year through 2020

✓GOAL: Non-Automotive
Increase non-automotive markets by 25% per year through 2020

✓GOAL: Productivity
Enhance productivity by 5% each year through 2010 and 8% by 2020

✓GOAL: Quality
Achieve six-sigma quality for all components by 2005; achieve AGMA 9 by 2005 and AGMA 10 by 2020 at six sigma

✓GOAL: Energy & Environment
Reduce overall energy consumption by 50% by 2010 and 80% by 2020

✓GOAL: Time Compression
Reduce total time to market from two years to six months by 2010 and one month by 2020

✓GOAL: Human Resources
Increase university and technical school graduates entering the PM² industry by 500% by 2010

Key Challenges

Materials Challenges
- Insufficient knowledge of porosity-property relationships
- Shortage of thermophysical data for new materials

Processing Challenges
- Inability to compact to 100% density with dimensional accuracy at low cost
- Lack of 3D forming processes for large components

Cross-Cutting Challenges
- Lack of process models and in situ sensors for materials and process controls
- Shortage of non-intrusive sensor materials

Research Thrusts and Priorities

Materials

Powder Processing
Explore fine particle and nanocrystalline powders

Material Science
Improve understanding of powder microstructure-performance relationships

New Materials
Explore new materials to better understand properties, processes, and potential applications (fine structured, amorphous, etc.)

Composite Materials
Study method of cosintering composites with different materials

Processing

Strengthening and Finishing
Develop new energy efficient sintering techniques

Manufacturing Science
Minimize process interruptions to move to more continuous production

Forming
Non-traditional processing techniques

Advanced Compaction
Methods to achieve full density with tight dimensional tolerance cost effectively

3-D Forming
Rapidly form complex 3-D components (selective laser sintering, rapid prototyping)

Rapid Manufacturing
Systems for more rapid manufacture of products

Equipment and Tooling
Increase automation, uptime, and speed

Enabling

Modeling
User-friendly math-based process models

Sensors and Controls
Use new or existing sensor technology in innovative ways

Design Tools
Develop a web-based design advisor

Testing and Demonstration
Establish agile PM² test-bed facility to gather data

Standards
Develop standards closer to actual application

R&D Structure
Form collaborative partnerships with other industries and government

Technology Planning Logic Flow

5 Enhanced Material Properties and Performance

The performance and value of PM² components starts with the materials from which they are made. The industry is on an unending mission to improve the properties and performance of the materials they offer customers. Combining the experience the industry has with traditional metals such as iron, copper, and tungsten with ongoing developments in other areas of material science including biological materials, plastics, and composites will lead PM² to a revolutionary new portfolio of material capabilities. Advanced materials will be combined with advances in processing and enabling technologies to deliver the highest-value components and systems to customers.

Strategic Goals

Enhancing material properties and performance will have far-reaching impact on the PM² industry. The research described in this chapter is primarily directed at achieving the goals for market growth described in Chapter 3:

✓GOAL **Achieve 12% annual market growth in automotive market through 2020.**

✓GOAL **Achieve 25% annual market growth in non-automotive markets through 2020.**

Material capabilities are an essential part of the overall PM² technology strategy. Enhanced material capabilities, including incorporation of different material types such as plastics, biological materials, ceramics, with traditional metal powders will enable PM² companies to penetrate entirely new markets which today have only limited exposure to the benefits of PM². At the same time, new material capabilities (functionally gradient material systems, for example) will also be used to continue to provide the automotive and other existing markets with innovative solutions to the technical challenges they will face over the next two decades.

Critical Barriers

For the PM² industry to enhance its material capabilities and achieve the goals for market growth, several technical barriers must be overcome. Overcoming these barriers successfully (shown in Exhibit 5-1) will enable the industry to develop new material capabilities that can expand the properties and performance PM² companies can offer customers.

One fundamental barrier in materials development is the incomplete knowledge of relationships between material properties and performance. Such knowledge will enable production of PM² components to achieve specified performance criteria with greater efficiency of material. New components can then be designed using knowledge of how performance is dictated by the microstructure of the material rather than in the iterative and empirical approach that is used today. Another barrier is the inability to manufacture composite materials at high volumes while achieving competitive costs. Currently composite materials are expensive to produce and are only done so in small volumes. Developing

Exhibit 5-1. Enhanced Material Properties and Performance – Critical Barriers

MATERIAL SCIENCE

- **Insufficient knowledge of porosity-property relationships**
- **Incomplete knowledge of relationships between material phases/constituents, properties, and performance**
  - Uncertainty with assumptions made in materials characterization
- **Inconsistent understanding of material science (in its application to particulate materials) throughout the industry**

INNOVATIVE MATERIALS

- **Shortage of thermophysical data, specifically for new materials**
- **Resistance to the qualification of new materials and processes due to lack of standards and material property data**

COMPOSITE MATERIALS

- **Inability to manufacture large volumes of composite materials at low cost**
- **Lack of methods to sinter functional laminates**

POWDER PROCESSING

- **Difficulties controlling critical powder characteristics (e.g., surface contamination, size distribution, etc.) during powder production**
  - Inconsistency and limited repeatability of powder production
- **Inability to process, handle, and monitor fine powders**
  - Problems include flowability, mixing, and health and environmental concerns
- **Lack of standards for blending powders**

manufacturing capabilities to produce such materials in larger volumes while maintaining cost competitiveness will help PM² take advantage of the promising market opportunities offered by composites.

Research and Development Needs

Overcoming the barriers and realizing the goals will require significant investment in research and development aimed at enhancing material properties and performance. Materials R&D activities have been organized into four areas: material science, innovative materials, composite materials, and powder processing. Fundamental material science research is needed to cultivate a better understand how material properties affect component performance in particulate materials. Innovative materials will enable market expansion by expanding the portfolio of material options PM² companies can offer their customers. Targeted research to understand the behavior of composite materials and their interaction will help ensure the unique nature of the P/M process is fully realized through the use of composite material systems. Improving powder processing will enable materials to be produced more quickly and accurately while reducing costs and improving efficiencies.

The detailed R&D needed in each area is shown in Exhibit 5-2, organized by time frame with high-priority needs shown in **bold**. Below is a brief description of each research area.

Material Science

A thorough understanding of particulate material science is critical to achieving exceptional part performance through enhanced material properties. The interaction of blended materials, thermophysical data, and porosity-property relations represent a small sample of the areas in which the PM² industry must improve its knowledge. Gaining a thorough understanding on these and other material science issues will provide the industry with greater control over critical powder characteristics while broadening the potential range of PM² applications.

PRIORITY **Improve understanding of the relationships among processes, microstructure, and performance.** Such understanding will enable PM² companies to optimize material selection and process configuration to achieve desired performance.

Innovative Materials

The development of innovative materials is paramount to maximizing the future growth and success of the PM² industry. With new materials comes a tremendous variety of new applications, opening opportunities previously unavailable to PM² companies. Concurrently, new materials will allow companies to better serve current customers through the substitution of superior materials into existing applications. Innovative material systems are also a key part of the future of the PM² industry, with fully engineered, functionally gradient, and other material systems that put the "right material in the right place" serving unique customer needs.

PRIORITY **Develop a better understanding of properties, processes, and potential applications for innovative materials.** Better-understanding new material types and combinations will enable the PM² industry to pursue advances such as fully engineered systems, functionally gradient components, and fine-structured and amorphous materials.

PRIORITY **Generate materials for use in alternative-power vehicles (e.g., fuel cell, hybrid, etc.); evaluate magnetic materials production**. Because the automotive industry is a primary customer of the PM² industry, pursuing technical advances to coincide with the future direction of the automotive marketplace is crucial to sustaining this important PM² market.

Composite Materials

Composite materials production is a specialized branch of PM². Presently, many PM² companies are unable to manufacture composites at high-volumes cost-effectively. The nature of the P/M process is suited ideally to composite materials because material placement in component systems is controlled more easily. Experimentation with composite materials will eventually allow the industry to produce custom-made powders that combine metals with biological materials or plastics for the most demanding end-use applications.

PRIORITY **Study methods to co-sinter composites with different materials**. Co-sintering to strengthen the different materials within a composite is a priority for the industry to position it to take advantage of this promising market opportunity.

Powder Processing

Powder processing involves not only powder manufacture, but also handling and blending. Optimizing each of these steps ensures the highest powder quality and consistency is achieved. Producing fine powders will become increasingly important as customers demand nanoscale components, and as a strategy to push component densities and tolerances higher. Powder mixtures presents their own set of challenges which must be addressed as demand increases for composites and multi-functional component systems.

PRIORITY **Research the compaction, material properties, and sintering of fine particles and nano-crystalline powders**. Ultimately, production of sub-micron powders in large volumes is sought.

Research and Development Priorities

While all of the R&D described in Exhibit 5-2 is important to expanding material capabilities within the PM² industry, two of the needs have been identified as highest priority by the industry. These items, along with the top-priority needs from Chapters 6, and 7, are discussed in detail in Chapter 8, including their potential impact on the six goals and preliminary development of an implementation path. The top-priority materials research needs are:

TOP PRIORITY **Develop new materials, processes, and material combinations to create new material capabilities** (including totally engineered, fine powder and nano-crystalline, magnetic, bio-compatible, and functionally gradient materials).

TOP PRIORITY **Conduct fundamental material characterization studies for existing and new materials to determine properties, structure, and performance relationships.**

These research activities will help address some of the most critical technical barriers in the materials development area, and the technological breakthroughs sought have the potential to make substantial contributions towards market growth goals as well as lesser impacts on the five technical goals.

Exhibit 5-2. Enhanced Material Properties and Performance - R&D Needs

Enhanced Material Properties and Performance

	Near-Term (2001–2004)	Mid-Term (2004–2010)	Long-Term (2010–2020)
Material Science	**Understanding of process-microstructure-performance relationships** Research material properties between 90% and full density Thermophysical data development	Fundamental porosity-property studies Biomedical materials research Research organic powder interaction (metal-powder interface) Ability to predict properties from microstructure Study compatibility of functionally gradient materials	Customize products based on application of material science principles
New Materials	**Materials for alternative fuel vehicles (fuel cells, hybrid, etc.)** New materials development using existing technology Novel alloy production Low-creep, high-temperature materials Property data for light-weight materials (MMCs)	**Understand new material properties, processes, and applications (100% engineered materials, functionally gradient materials fine structured, amorphous, metallic glasses, etc.)** Materials single-pressed to full density Material with elastic modulus 50% greater than steel Self-sintering powders	**Innovative magnetic materials**
Composite Materials	Study the feasibility and performance/cost benefits for composites producible from powders Methods to add value to structures in the P/M phase	**Co-sintering composites with different materials** Low-cost composite materials applications	Custom composite powders of different materials (biological, plastics, etc.)
Powder Processing	Novel approaches to conventional powder manufacture Assess powder measurement techniques using inter-laboratory testing Fine, clean powder use to facilitate full density Powder handling technology as it relates to powder uniformity	**Fine particle technology and nanocrystalline powders** - compaction - material properties - sintering Improved atomization technology (particle size distribution) Blending and dispersal methods for powder mixtures Research particle reactions, intense atomization processes for droplet control (in situ composites with tolerance control)	Economic manufacture of sub-micron particles at production scale

6 Improved Manufacturing and Processing

Manufacturing and processing has been the basis for the PM² industry's success over the past 50 years. Because the P/M process can be used to produce components and engineered systems that offer higher value than other metal forming processes, the process itself and how it is applied has been the real source of competitive advantage. Building on this advantage by pursuing the technologies outlined below is essential in maintaining that edge. The P/M process must be integrated with technical advances in materials as well as enabling technologies such as sensors and modeling to ensure the most sophisticated process is being used to deliver value to customers.

Transforming the PM² industry into an advanced manufacturing industry is one of the most significant challenges the industry faces today. Achieving rapid manufacturing rates while also improving quality and dimensional control and expanding the range of sizes and complexity for PM² components is the challenge. A broad range of R&D needs described in this chapter will help the industry meet that challenge.

Strategic Goals

Improving manufacturing and processing will help the PM² industry realize several of the technical goals outlined in Chapter 4. The research described below is aimed to develop many new capabilities that will make significant progress towards all of the industry goals, but most directly impact the following three goals:

✓GOAL **Enhance productivity by 5% each year through 2010 and 8% through 2020.**

✓GOAL **Achieve six-sigma quality for all components by 2005; improve tolerances to achieve AGMA 9 by 2005 and AGMA 10 by 2020 at six sigma.**

✓GOAL **Reduce overall energy consumption by 50% by 2010 and 80% by 2020.**

Improvements in manufacturing science, processing techniques, and supply chain integration will propel the industry to a position of enhanced competitiveness in new and existing markets, and thus the research described in this chapter will also have a secondary affect on the market and other goals.

Critical Barriers

To achieve the goals of improving productivity while improving quality and precision and reducing energy consumption, significant technical advances will be required. Exhibit 6-1 lists several critical barriers that today limit the manufacturing and processing capabilities of the PM² industry. Addressing and overcoming the barriers through strategic technology development will determine the success of the industry in realizing aggressive market growth over the next 20 years.

Exhibit 6-1. Improved Processing and Manufacturing – Critical Barriers

Manufacturing Science

- **Limited size range in component forming and processing**
- **Property variation within parts**
  - Lack of methods to measure critical variables such as density inhibits greater part uniformity
- **Inability to predict the long-term behavior and consistency of a part produced from a given batch**
- **Difficulties creating controlled porosity**
  - e.g., biomedical, lightweight, telecommunications, and other applications.
- **Tendency to develop point solutions rather than underpinning technologies for multiple applications**

Advanced Compaction

- **Inability to compact to 100% density with tight dimensional control and accuracy at low cost**
  - Presence of residual pores in PM^2 parts
- **Excessive use of and ineffective lubricants**
  - Insufficient friction reduction adversely effects compaction energy, energy gradients, and size
- **High frequency of green density variations**
  - Component complexity is accelerating faster than equipment control methods

3-D Forming

- **Lack of efficient, accurate, and cost-effective 3-D forming process for large components**

Strengthening & Finishing

- **Lack of predictability in current sintering methods**
- **Inadequate alloys and finishing processes to provide superior corrosion resistance**
- **Unknown correlation between surface and near-surface properties as a function of finishing processes**

Rapid Manufacturing

- **Inability to utilize rapid manufacturing in production**
- **Sintering process can be time consuming**
- **Inability to rapid prototype to production-level tolerances**

Equipment and Tooling

- **Inability to process increasingly complex shapes while adhering to more strict design tolerances**
- **Increasing capital intensity in relation to sales**

Waste Reduction

- **Lack of scrap and waste recycling technologies (e.g., planned design and separation technology)**
- **Meeting current and future environmental regulations**

Among the most critical barriers the industry faces are the limited size range and complexity of components PM² companies can produce cost effectively. While expanding the range of components PM² technology can produced, the industry must also be ready to meet customer's demand for quality of those components. PM² technology must improve to make achieving full or near-full density more cost efficient. Additionally, strengthening and finishing operations such as sintering are unpredictable and energy intensive. Optimizing or in some cases eliminating the need for sintering operations is a critical need for the industry.

Research & Development Needs

Overcoming the challenges and achieving the goals will require significant investment in research and development to improve the manufacturing and processing capabilities of PM² companies. The technology needed to push manufacturing and processing to the next level of speed and precision has been categorized into the following seven areas:

- Manufacturing Science
- Advanced Compaction
- Equipment and Tooling
- Waste Reduction
- Rapid Manufacturing
- 3-D Forming
- Strengthening and Finishing

The R&D needed in each area is described in more detail below and in Exhibit 6-2. The research needs are organized by time frame over the next 20 years and high-priority needs are shown in **bold**. Each of the categories above contains one or several needs critical to improving manufacturing and processing capabilities for PM² companies.

Manufacturing Science

Improvements in manufacturing and processing begin with a better understanding of manufacturing science. A more complete fundamental understanding will lead to better process methods and design, improved efficiencies throughout the manufacturing process, and ultimately innovative processing techniques that accomplish what current technology does today and much more with superior performance.

PRIORITY **Minimize process interruptions (starts and stops) to move towards more continuous production.** As PM² manufacturing science is refined, the starting and stopping that is typical of today's PM² processes can be minimized, increasing productivity, reducing time requirements, and improving quality.

Advanced Compaction

Advanced compaction techniques will allow PM² producers to improve the density of their components, ultimately achieving fully dense components that perform better than components produced using today's best technology. However, full density must be achieved while maintaining or improving the tight dimensional control and cost-effectiveness that customers have come to expect from PM² components. In the long term, technology breakthroughs may lead to step-change improvements in processing and manufacturing efficiencies.

PRIORITY **Develop more easily removed, slicker die lubricants; develop wear-resistant die materials or coatings to reduce lubricant requirements.** These two R&D priorities are aimed at achieving the same end result: improved debinding to minimize the drawbacks with using lubricants during component production.

PRIORITY **Develop material and process systems to eliminate residual porosity cost effectively while maintaining dimensional tolerances.** Powder design, improved lubricants, high-density compaction, and enhanced sintering techniques are all key components which must be considered in pursuit of this research priority.

PRIORITY **Develop approaches to reduce process variations to improve quality and efficiency.** Eliminating variations which currently limit quality and precision of PM² components will ensure PM² companies can continue to meet stringent quality demands.

3-D Forming

Conventional press-and-sinter technology has provided the foundation for the PM² industry. However, because of the nature of the process, components can only be formed and therefore designed with two dimensions of flexibility, the third dimension being reserved for the pressing operation. Three-dimensional forming, or 3-D forming, is the term used to describe eliminating the two-dimensional design constraint and allowing three degrees of design and forming freedom. While some 3-D forming techniques such as metal-injection molding (MIM) and hot isostatic pressing (HIP) are used for certain applications, they can only achieve cost-effectiveness for a limited range of materials or have component size and complexity limitations.

PRIORITY **Explore the critical factors for 3-D forming** (filling, pressing, and tooling techniques; low-friction materials; and improved lubricants affecting size limitations).

PRIORITY **Develop capability to rapidly form complex 3-D components with high density and tight dimensional control.** Ultimately, 3-D forming must be as quick as current 2-D technology allows, with similar or greater quality and tolerance control.

Strengthening and Finishing

After a component is formed, strengthening and finishing operations can be used to give the component the properties needed to meet customer needs, such as strength, specific metallurgical qualities, and surface finish. These processes are among the highest energy-consuming stages in PM² processing and represent a significant opportunity for efficiency gains by improving the processes or in some cases eliminating certain strengthening and finishing steps all together.

PRIORITY **Develop sintering aides to improve efficiency**; **develop sintering techniques that transfer energy to the component more rapidly** (e.g., microwave sintering); Because sintering is one of the most energy-intensive processes PM² companies use to create components, these priorities have the potential to contribute significantly to the goal of reducing energy consumption.

PRIORITY **Develop improved heat treating processes** (e.g., induction, laser heating) to improve the energy efficiency, speed, and accuracy of such techniques.

Rapid Manufacturing

Rapid manufacturing is essential for the PM² industry to meet rapidly changing market requirements by delivering quality PM² components faster than the competition. Reducing time to market directly increases the value PM² companies can offer their customers.

PRIORITY **Develop systems to enable more rapid manufacturing,** including rapid tooling capabilities.

Equipment and Tooling

Equipment and tooling is a key component to many of the areas of research in this chapter. However, several R&D needs relate specifically to improving equipment and tooling, such as reducing time to market and improving quality. Improving the speed and capacity of existing equipment to increase output while avoiding capital expenditures and developing diagnostic methods to monitor product quality will improve PM² industry's capabilities in this area.

Waste Reduction

Waste reduction technologies will help the PM² industry improve its cost-effectiveness while also making gains in environmental performance. Reducing scrap and other process wastes will help PM² companies realize the full potential of their processes in delivering value to customers. In addition, improved recycling of PM² components will help regain value from components which have reached the end of their intended lifetime.

Research and Development Priorities

While all of the R&D described above is important in bringing PM² manufacturing and processing to a higher level of sophistication, three of the needs have been identified as highest-priority. These items, along with the top-priority needs from Chapters 5 and 7 are discussed in detail in Chapter 8, including their potential impact on the six goals and preliminary development of an implementation path forward. The top-priority manufacturing and processing research needs are:

TOP PRIORITY **Develop 3-D forming processes that exploit advanced pressing, tooling, low-friction materials, lubrication, and fill technology.**

TOP PRIORITY **Develop material and process technology to achieve 100% density while maintaining dimensional tolerances and cost-effectiveness.**

TOP PRIORITY **Minimize process interruptions to move to more continuous production.**

These research activities address some of the most critical technical barriers facing manufacturing and processing, and the technological breakthroughs sought have the potential to have a strong impact on the six strategic goals of the industry, particularly the goals for market growth, productivity, and energy/environment.

Improved Processing & Manufacturing

	Near-Term (2001–2004)	Mid-Term (2004–2010)	Long-Term (2010–2020)
Manufacturing Science	Accurate, rapid measurement of localized green properties Novel applications of current processing techniques Higher efficiency furnace designs (productivity and energy)	**Minimize process interruptions to move to more continuous production** Understanding of basic process phenomena Understanding of density variation impacts on tolerances Manufacturing process flexibility	Form and sinter in one process
Advanced Compaction	**More easily removable, lower-friction lubricants** **Wear-resistant die materials or coatings** **Material and process systems to eliminate porosity cost effectively with tight tolerances** (powder design, reduced lubricants, higher-density compaction, and enhanced sintering) Improved MIM part debinding Low-cost compaction devices	**Reduce process variations to improve tolerances** Materials and processes to make large and small parts economically Improved welding and joining techniques Methods to tailor powder fill - increase powder fluidity/uniformity - decrease lubricant use	Non-traditional processing techniques
3-D Forming	**Research factors critical to 3-D forming** - filling, pressing, and tooling - low-friction materials, improved lubricants	**Rapid formation of complex 3-D components with high density and tight dimensional control** - as fast as current 2-D technology Binder research - high metal-binder ratio - cold-form spherical powders - complete binder removal	New techniques for large 3-D components - plastic molding - sintering - infiltration

	Near-Term (2001–2004)	Mid-Term (2004–2010)	Long-Term (2010–2020)
Strengthening and Finishing	**Sintering aids to improve efficiency** - low-cost production of coatings for powders to aid sintering Improved green compacting and sintering	**New sintering techniques with rapid energy transfer (e.g., microwave)** **Improved heat treatment (induction, laser, etc.)** Engineered surface properties through heat treatment Machining cost reduction	Processes and materials that eliminate sintering and de-lube
Rapid Manufacturing	**Systems for more rapid product manufacturing** Rapid tooling capabilities		Rapid product development cycles (from concept to finished component in less than one week)
Equipment and Tooling	Improve equipment speed and capacity to improve capacity utilization Low-cost, low-volume, quick-change tooling Diagnostic methods that ensure equipment is yielding consistent product	Advanced equipment and tooling - increased uptime - completely automated - minimal maintenance	
Waste Reduction	Improved process scrap recycling and utilization Process waste reduction technology	Lower gas and atmosphere consumption Robust multi-gas analyzers for dirty environments	

7 Enabling Technologies and Infrastructure

Improvements to PM² material and manufacturing capabilities are not enough by themselves to propel the PM² industry to the level of technological sophistication that will be required to sustain aggressive growth rates through 2020. These developments must be coupled with the most advanced enabling technologies available, such as design tools, modeling, in situ sensors, controls, and diagnostics to ensure optimal application and operation of those advanced material and manufacturing capabilities.

Conducting and overseeing the overall PM² industry research program will require a stable and comprehensive infrastructure that combines the unique capabilities of individual and groups of PM² companies, public and private research institutions, and government into a broad partnership that can not only coordinate technology development, but also provide the human and financial resources needed to sustain the research effort over the long term. The needs of the entire industry will only be met through collaboration among these diverse sectors of the industry.

Strategic Goals

Developing enabling technologies and the necessary infrastructure will allow the PM² industry to achieve their technical and market goals. The research described below is aimed to develop new capabilities that will lead to significant progress towards all of the industry goals, but most directly impact the following two goals:

✓GOAL **Reduce total time to market from two years to six months by 2010 and one month by 2020.**

✓GOAL **Increase university and technical school graduates entering the PM² industry by 500% by 2020.**

Because enabling technologies permeate almost every aspect of PM² processes, the R&D described in this chapter will have a lesser impact on the other technical goals described in Chapter 4.

Critical Barriers

Exhibit 7-1 lists several critical barriers that must be overcome to achieve these goals. Addressing the barriers through strategic technology development will determine the success of the industry in supplying components quickly as well as fueling the desired industry growth with the necessary expertise and talent.

Among the most critical barriers the industry faces are the limited process and material modeling capabilities, lack of closed-loop controls, and the absence of global, uniform design standards for PM². In addition, the flow of human expertise into the industry is limited for several reasons, including inadequate public relations efforts.

Exhibit 7-1. Enabling Technologies and Infrastructure – Critical Barriers

MODELING

- **Inadequate material and process modeling capabilities (e.g., pressing and sintering)**

SENSORS, CONTROLS, AND DIAGNOSTICS

- **Lack of in situ sensors for closed-loop controls and quality assurance**
  - Inability to measure internal cracks in green parts online
- **Limited process and product control methods**
  - Lack of sensors to optimize gas supply systems and gas use during sintering
  - Inefficient temperature control for both process heat removal and addition
- **Lack of adequate diagnostic methods to evaluate powder fill and green parts**

DESIGN TOOLS

- **Lack of an integrated database to assist designers in achieving desired performance characteristics**
  - Lack of fundamental phase equilibrium and other data to optimize powder and product design

TESTING AND DEMONSTRATION

- **Insufficient effort to promote PM² industry as a manufacturer of unique parts with unique properties**
  - PM² often perceived as offering poorer properties regarding strength, fatigue, toughness, wear, etc.
  - Customers unaware of all PM² capabilities
- **Lack of accelerated testing and long-term testing data**

SUPPLY CHAIN INTEGRATION

- **Incomplete interface between powder maker, equipment/tooling suppliers, powder user, and final customer**
  - Inadequate communication of customer powder/component property needs
  - Long-lead time for customer acceptance
- **Lack of concurrent engineering with customer**

STANDARDS

- **Absence of global, uniform design standards and data**
- **Lack of electronic communication standards (XML) to facilitate supply chain integration**

INDUSTRY RESOURCES

- **Insufficient investment in powder material technology and capital equipment**
- **Limited network of knowledge**
  - Lack of strategic alliances between powder, equipment, component, and customer companies
- **Limited success in attracting qualified technical and professional staff to the industry**
  - Limited resources and incentives
  - Inadequate resources available for education

R&D STRUCTURE

- **Limited R&D funding (basic and specialized PM² applications)**
  - Prolongs cutting-edge innovation and market expansion
- **Minimal information sharing throughout different sectors of the PM² industry**
  - Inhibits coordinated industry-wide R&D initiatives
  - Shortage of partnerships among small companies within the PM² industry
- **Industry's inability to escape near-term mindset for R&D**

Research & Development Needs

Over the next 20 years, the PM² industry must pursue a variety of R&D strategies to surmount critical barriers preventing the evolution of its enabling technologies and infrastructure. These R&D needs have been categorized into eight important areas:

- Modeling
- Design Tools
- Supply Chain Integration
- Industry Resources
- Sensors, Controls, and Diagnostics
- Testing and Demonstration
- Standards
- R&D Structure

Each of these areas contains several specific research needs in the near- (0-3 years), mid- (3-10 years), and long-term (>10 years) time frames and high-priority needs are shown in **bold** below. A more thorough explanation of each area and its associated R&D priorities is provided below and outlined in Exhibit 7-2.

Modeling

The modeling of parts and processes alike is fundamental to the development of more sophisticated and reliable PM² processing techniques. Such models will provide valuable insight into component performance over its lifetime before it is produced, in addition to allowing process optimization through both off- and on-line simulation.

PRIORITY **Create user-friendly, mathematical models to assist in process optimization.** Modeling mechanisms must be user-friendly, use realistic constraints, and be readily available throughout the industry.

Sensors, Controls, and Diagnostics

The optimal use of sensors, controls, and diagnostics will help enable the industry to harness the full potential of the P/M process. A balanced approach including developing new sensor and control technologies while continually exploring innovative uses for current sensor and control mechanisms will help to provide both near- and long-term solutions. By cultivating a more complete understanding of basic process phenomena and reducing process inefficiencies, defects, and variations using the information provided by sensors, controls, and NDE diagnostics, the PM² industry can significantly further its reputation as offering an advantageous, reliable means of component manufacture.

PRIORITY **Explore novel uses of new or existing sensor technologies** to monitor particle size, particle size distribution, flow rates, presses, and furnaces.

PRIORITY **Develop system-based, closed-loop feedback controls to enhance problem traceability** (e.g., problems in sintering feed back to earlier process).

Design Tools

The creation of design tools for PM² components is crucial not only for improving design capabilities, but also to educate a broader range of designers about the unique and beneficial performance PM² components can offer. Because such design tools are lacking, designers often use tools developed for other materials and metal forming processes to estimate PM² component options, or simply do not consider PM² components at all, creating a severe competitive disadvantage for the industry.

PRIORITY **Develop an Internet-based design advisor** incorporating tools for material selection, process selection, design rules, part performance, and error budgets.

Testing and Demonstration

Via testing and demonstration initiatives, the PM² industry can learn much about the performance of both its existing processes and newly developed technologies such as sensors, controls, and NDE diagnostics. Improving the availability of such demonstration facilities will accelerate technology deployment throughout the industry.

PRIORITY **Establish an agile PM² testing facility for gathering data.** Facilities should include a demonstration test bed for process models, sensors, and diagnostics integration.

Supply Chain Integration

Supply chain integration will allow PM² powder suppliers, equipment and tooling providers, and component manufacturers to work more closely together to meet customer needs swiftly and accurately. Working together will allow the entire design and manufacturing process to be optimized to ensure the best powder, tooling, and manufacturing processes are used to meet customer requirements, and that it is done at record speed.

Standards

In order for PM² components to gain wider acceptance in the marketplace, continued and expanded industry-wide standards on material properties and component performance criteria are needed. New standards should be closely linked to actual applications to ensure their practicality and appropriateness, using the most accurate data possible to provide realistic constraints. As PM² companies continue to expand global markets, international and global standards will become increasingly important.

PRIORITY **Accelerate and expand the development of uniform property standards for materials and parts.** These standards should ideally be global.

Industry Resources

Every R&D initiative is dependent on the security of PM² industry resources. The industry must establish and maintain a framework that encourages information sharing, education, proactive thinking, and financial support. The inability to successfully pool its collective resources will place the PM² industry at a severe disadvantage when targeting new or increased market shares in what are becoming increasingly competitive environments.

R&D Structure

A sound R&D structure is essential to foster and utilize creative ideas. Without an environment that nurtures innovative thinking, novel solutions to problems plaguing the industry are realized inefficiently or lost entirely. Reduced time-to-market (from concept to implementation) places a greater burden on the PM² industry to soundly establish itself on the cutting-edge of part design and manufacture. Moreover, missed opportunities or failures in new markets cannot be afforded, and would result in major setbacks for the industry.

PRIORITY **Create a more nurturing environment for the formulation and implementation of innovative ideas** by establishing additional multi-disciplinary university consortia.

Research and Development Priorities

While all of the R&D described above is important for incorporating enabling technologies into PM^2 processes sophistication, one of the needs has been identified as highest-priority. This item, along with the top-priority needs from Chapters 5 and 6 are discussed in detail in Chapter 8, including their potential impact on the six goals and preliminary development of an implementation path forward. The top-priority enabling technology research need is:

TOP PRIORITY **Develop integrated process models, sensors, and NDE diagnostic methods to reduce variations and improve tolerances and efficiencies.**

This need helps to address some of the most critical technical barriers in the enabling area, and the technological breakthroughs sought have the potential to have a strong impact on the six strategic goals of the industry, particularly the goals for market growth, time compression, and quality.

Enabling Technologies & Infrastructure

2001 — Near-Term — 2004 — Mid-Term — 2010 — Long-Term — 2020

Modeling

Near-Term

- Process modeling for pressing, sintering, gas flow in furnaces, and other processes
- Supply chain for integration
  - use with e-business

Mid-Term

- **Widely available user-friendly, math-based process models with realistic constraints**
- Modeling of degradation during service life
- "Virtual reality" 3-D plant simulation for use in design, scale-up, and education

Long-Term

- Complete predictive mechanism of component degradation and critical failure mechanisms
- Modeling of complete forming and strengthening processes for a component

Sensors, Controls, and Diagnostics

Near-Term

- Understanding of critical parameters to monitor and interrelationships for quality
- Enhanced control over powder uniformity
- Advanced controls for more more accurate green compacting and sintering
- Low-cost diagnostics techniques to rapidly evaluate critical performance characteristics of powder and green components
- Non-intrusive, stable sensor materials for process control

Mid-Term

- **Novel use of new or existing sensor technology to monitor particle size, particle size distribution, flow rates, and furnace conditions**
- **System-based, closed-loop feedback controls** (sintering problem feeds back to earlier process)

Long-Term

- Robust multi-gas analyzers for dirty environments

Design Tools

Near-Term

- Designer education (at school and on-the-job mentoring)
- Risk management tool for designers

Mid-Term

- **Internet-based design advisor**
  - material selection
  - process selection
  - design rules
  - performance
  - error budgets

Long-Term

- Free-form manufacturing design tool and device (build part particle by particle, no tooling)

Testing and Demonstration

Near-Term

- **Establish agile PM² test-bed facility for gathering data**
  - demonstration test bed for integration of process models, sensors, and NDE diagnostics
- Improved availability of pilot-scale facilities

Mid-Term

- Demonstration projects using integrated design teams across companies
- Accelerated life-cycle testing methods

	Near-Term (2001–2004)	Mid-Term (2004–2010)	Long-Term (2010–2020)
Supply Chain Integration	Time-to-market scheme more responsive to customer demand Improved communication among supply chain, end users, and R&D personnel	Modeling and e-business for supply chain integration Design and implementation of electronic communication standards (XML)	
Standards	**Accelerated property standards development (including global standards)**	**Standards development that considers application** New standards based on most accurate process data available	
Industry Resources	Increased commitment to R&D Internet-based education program Increased technology demonstration support Assessment of industry-wide long-range resource planning Widespread knowledge of competing technologies	Cost-effective funding sources for R&D and capital formation Structure for PM^2 R&D venture capital and equity to be funded by industry, for industry Education programs (textbooks) for composite materials, new materials, and new processes	Accurate prediction of needed properties, tolerances, and human resources
R&D Structure	**Nurturing environment for formulation/implementation of innovative ideas** Multi-disciplinary university consortia	Collaborative partnerships with other industries (e.g., finishing industry, lubricant manufacturers, ceramics industry, fiber-reinforced material producers, etc.)	

8 R&D Priorities and Implementation

The overall research strategy for the PM² industry must be implemented in a balanced manner, focusing on near-term successes without neglecting mid- and long-term goals. Activities are best pursued through collaborative partnerships both within the industry and with relevant government programs, private research organizations, and the academic community. The needs outlined in this roadmap can be properly addressed only through collaboration and leveraging of limited R&D resources.

The technology outlined in this roadmap, if successfully developed and implemented, will help position the PM² industry for success in reaching its goals and remaining competitive in future markets. While each R&D need presented is important to the industry, six top-priority research areas emerge. These top-priority R&D needs, selected from across the three research areas described in Chapters 5-7 and described below, have the potential to substantially impact several or all of the industry's strategic goals and position it for success over the next 20 years and beyond. The descriptions below also indicate areas of potential collaboration among not only PM² companies, but also with government and other potential partners such as private research organizations and universities.

Top-Priority Research Needs

- Develop 3-D forming processes and exploit advanced pressing, tooling, low-friction materials, lubrication, and fill technologies
- Develop material and process technologies to achieve 100% density while maintaining dimensional tolerances and cost-effectiveness
- Develop innovative materials, processes, and material combinations to create advanced material capabilities
- Develop integrated process models, sensors, and NDE diagnostics that tie industry together from user to supplier to reduce process variation, improve tolerances, and improve process and supply chain efficiencies
- Conduct fundamental characterization studies for new materials: determine property-structure-performance relationships
- Minimize process interruptions to move to more continuous production

R&D PRIORITY

Develop 3-D forming processes and exploit advanced pressing, tooling, low-friction materials, lubrication, and fill technology

IMPACT ON GOALS

DESCRIPTION

One of the major limitations of traditional press-and-sinter technology is that there are only two dimensions of design freedom, with the third reserved for pressing direction. While some 3-D consolidation technologies exist (e.g., MIM, HIP), they are not economical for the majority of components produced today. Developing the capability to design and form PM² components in three dimensions as quickly and economically as today's 2-D technology is a technical challenge that will have huge implications for market expansion and time-to-market. The degree of technical challenge in developing 3-D forming technology is extremely high; accordingly, a wide-reaching collaborative partnership involving many different representatives from various industry and related institutions is appropriate.

KEY TECHNICAL ELEMENTS

- Tooling design and techniques
  - modeling
  - coatings
  - finite element analysis
  - time compression
  - adjustability
  - soft tooling
- Processing design and techniques
  - isopressing
  - solid free-form fabrication
  - magnetic fabrication
- Binders
- Rapid prototyping
- Low-friction materials
- Lubrication
- Fill methods
- Powder design; powder density
- "Monster" MIM
- In situ non-destructive evaluation (NDE)
- Sintering time reduction
- Press automation
- Demonstration mechanism
- Furnace design
- Gas flow modeling

IMPLEMENTATION

PM² ROLE

- Resource integration/allocation
- Testing facilities
- Identify priorities/applications
- Cost-benefit evaluation
- New process and technology development

GOVERNMENT ROLE

- DOD–Military aircraft and tank applications; part configuration
- NIH–Medical implants
- Navy–On-board fabrication
- DOE–Rapid prototyping of fill methods
- NDE capabilities at DOE labs
- NASA–Construction materials; lightweight materials
- NIST/ATP–Facilitate vertical collaboration between powder makers, equipment providers, part makers, & OEMs
- Technical and financial resources (risk mitigation)
- Organization and funding of pre-competitive models

POTENTIAL PARTNERS

- Polymer and chemicals industries
- Universities
- MPIF, CISP, PMRC, and other industry groups facilities vertical collaboration among PM² companies and with end-users
- CPMT–Facilitate horizontal collaboration
- End-users willing to implement newly introduced technologies

R&D Priority

Develop material and process technology to achieve 100% density while maintaining dimensional tolerances and cost-effectiveness

Impact on Goals

Description

The density and residual porosity of a PM^2 component play a significant role in its quality and performance. Achieving the highest density possible is normally the goal, because as density is pushed higher the metallurgical properties of the structure approach that of wrought metal, which is considered fully dense. Not all current PM^2 applications require full density and accordingly PM^2 components have been successful. However, as densities are driven upwards, larger percentages of the overall fabricated metal products market can be overtaken by the PM^2 industry as the economic advantages of PM^2 processing techniques are applied to fully dense components.

Key Technical Elements

- New tooling materials and designs
- Isostatic pressing
- High-temperature sintering
- Liquid-phase sintering
- Self-organizing ("smart") powders
- Better equipment utilization
- High-performance press designs
- Powder lubrication systems
- Press cost reduction
- Ultra-compressible powders
- Powder morphology
- Surface treatments
- Particle size distribution
- Powder fill and flow
- Sensor and modeling
- Die-less technologies
- Non-traditional pressing techniques

Implementation

PM^2 Role

- Champion for new forming technologies
- Matching funds for projects
- Promotion of fully dense capability importance to government
- Provide system-level view to ensure technology can be implemented in real processes
- Provide testing facilities
- Technical and financial resources
- Cost-benefit evaluation

Government Role

- NIST (ATP), DOE, NSF, DOD, PTIA, Ben Franklin Technology Center
- Funding of lubricant, morphology, etc. studies
- Provide neutral, industry-wide platform
- Access and coordination of national laboratory expertise and testing facilities
- Assistance with risk mitigation

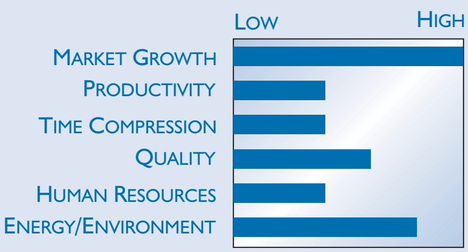
Potential Partners

- MPIF, CISP, PMRC, and other industry groups facilities vertical collaboration among PM^2 companies and with end-users
- CPMT–Facilitate horizontal collaboration
- End-users willing to implement newly introduced technologies
- Other industries using pressing technologies
- Universities
- International partners

R&D Priority

Develop new materials, processes, and material combinations to create new material capabilities

Impact on Goals



Description

Cultivating new material capabilities is essential for the PM² industry to expand and diversify its markets and realize its goals, particularly those relating to market growth. Specifically, material capabilities in the following areas are sought:

- fine particle/nano-crystalline powders and associated handling technology
- totally engineered, or "tailored", materials that put the right material in the right place
- multi-functional and functionally gradient materials
- magnetic materials for power systems in alternative vehicles
- bio-compatible materials
- composite materials

These developments will not only open up new market segments that hold promise for attractive profits and growth, but also help serve existing markets and customers by offering a broader range of components with advanced performance. Each of the areas of materials focus is strategic in that it capitalizes on the unique nature of the P/M process (namely, powder-based part formation).

Key Technical Elements

- Material classes
  - engineered materials
  - fine powder/nanocrystalline
  - magnetic
  - biocompatible
  - functionally gradient
  - multi-material systems
- Thermal/mechanical approaches; matching thermal expansion characteristics; thermal sprays; thermal compatibility of precursors
- Powder fill technologies
- Fine/reactive material handling
- Gradient blending design tools
- Suitable material combinations
- Functionality confirmation
- Feasibility demonstration
- Critical performance parameters
- Sensor technologies
- Spatial controls
- Environmental factors
- Standards development

Implementation

PM² Role

- Identification of market needs and applications
- Provision for resource integration and systems perspective
- Information sharing
- Powder producers
  - High-quality, specialized alloy supply
- Raw materials development
- Economic analyses
- Sintering studies
- Standards development

Government Role

- Test/pilot plant provision
- DOE–High-wear application analyses (e.g., mining)
- DOE/NIST–Sensors & controls
- NIST–Materials characterization and modeling
- NASA–Multi-functional materials; thermal barriers
- DOE–Materials applications
- NIH–Bio-compatibility studies
- ATP
- New material needs surveys
- National laboratory research

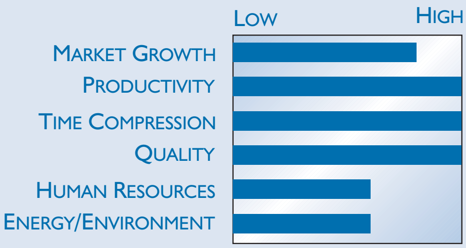
Potential Partners

- OEMs–Needs identification
- Non-traditional OEMs (e.g., bioengineering firms; university hospitals)
- Universities/research laboratories
- ASTM
- Component producers
- Sensor developers/manufacturers
- Automotive, aerospace, biomedical, and telecommunications industries
- Equipment suppliers
- Venture capitalists

R&D Priority

Develop integrated process models, sensors, and diagnostics to reduce process variations, improving tolerances and efficiencies

Impact on Goals



Description

Taking advantage of significant advances in modeling, sensors, controls, diagnostics, and information technologies will help PM² companies get the most out of their capital investments and process configurations. Because the PM² industry is becoming more capital-intensive, measures companies can take to improve productivity or time-to-market using existing investments are crucial to success. Additionally, enhancements in process modeling and control can help reduce variations in the process, and thus improve dimensional tolerances and overall process efficiencies. Such improvements have the potential to lead to significant cost savings, increasing the value of PM² components to their customers.

Key Technical Elements

- National testing facility
- Modeling verification
- Modeling expertise capability
- Net-shape manufacturing
- Sensor needs assessment to understand critical parameters
- Software development
- NDE diagnostic tools
- In situ online sensors
- High-temperature, high-strength sensor materials
- Database development; data collection for large-scale processes
- High-temperature sensors

Implementation

PM² Role

- Model verification
- Process and parameter definition (including sensor needs)
- Sensor technology application
- Test-bed provision
- Spark research interest
- Elimination of disconnect between existing work in labs/academia and industrial applications

Government Role

- National laboratories (software development)
- Provide national facility (e.g., DOE lab)

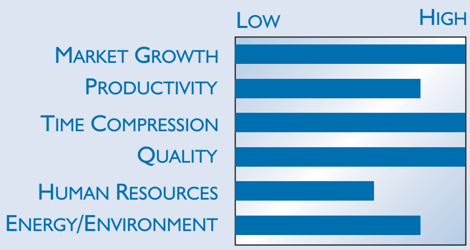
Potential Partners

- Universities
- Sensor manufacturers
- Software companies
- CTC
- MPIF, CISP, PMRC, and other industry groups facilities vertical collaboration among PM²
- Vertical collaboration between companies and end-users
- CPMT–Facilitate horizontal collaboration
- End-users willing to implement newly introduced technologies

R&D Priority

Conduct fundamental material characterization studies for existing and new materials to determine properties, structure, and performance relationships

Impact on Goals



Description

Understanding the relationships between material properties, microstructure, and component performance is crucial for component manufacturers and designers alike to be able to optimize a specific material or design. Particularly as new materials and material combinations are introduced into the PM² material portfolio, these relationships between properties and performance must be well understood and characterized. The data must be readily accessible — such data can be of significant use when convincing customers to consider PM² components as an alternative to current processes used, but without such data displacing existing manufacturing processes is difficult.

Key Technical Elements

- Thermodynamic properties
- Metallography
- Particle properties/ characteristics
- Static and dynamic mechanical properties
- Chemical properties
- Corrosion properties
- Handling and safety considerations
- Unknown/other aspects of novel materials (e.g., biological, etc.)

Implementation

PM² Role

- Data development
- Establishment of safe handling processes
- Material test specimen production
- Testing methods development

Government Role

- NIST
- National laboratories
- Thermophysical data development
- Information repository
- Regulator for safe handling
- Reference for testing standards

Potential Partners

- Universities
- Non-governmental organizations as information repositories
- ASTM
- CPMT
- PMRC
- Other industries
  - Ceramics
  - Polymers and chemical companies
  - Etc.

R&D Priority

Minimize process interruptions to move to more continuous production

Impact on Goals

Description

Current PM^2 processes require production to start and stop for several reasons, including equipment changeover, component handling, and maintenance. Such interruptions in production hinder PM^2 companies in their efforts to push productivities higher while reducing time to market. Process variations can also lead to quality variations and efficiency losses. Working to minimize these interruptions will have significant impact on several of the industry goals, including the potential to contribute to market growth by improving the overall value of PM^2 components to both existing and potential customers.

Key Technical Elements

- Total process automation
  - production
  - tooling
  - handling
- Sensors and controls to enable closed-loop feedback control
- Reduced equipment downtime
- Improved equipment speed
- Modeling of large and small component production

Implementation

PM^2 Role

- Resource integration/allocation
- New process and technology development
- Cost-benefit evaluations

Government Role

- Provide access to national laboratory capabilities
- Provide neutral industry-wide platform for collaboration
- Assistance with risk mitigation

Potential Partners

- ASTM
- CPMT
- PMRC
- Universities
- Vendors and technology providers

A Appendix: List of Contributors

Susan M. Abkowitz
Dynamet Technology, Inc.

Clare Allocca
National Institute of Standards and Technology

Allen M. Alper, Sr.
Alper Consulting Company

Gary L. Anderson
Keystone Powdered Metal Company

Iver Eric Anderson
Ames Laboratory

Diran Apelian
Metal Processing Institute

A. Elliott Archer
Metal Powder Products Company

John P. Barber
IAP Research, Inc.

Jeff Berlin
Hawk Corporation

Sherri R. Bingert
Los Alamos National Laboratory

Bruce Boardman
Deere & Company

Keith H. Boswell
Caterpillar Inc.

Robert Burns
Cincinnati Incorporated

Russell A. Chernenkoff
Ford Motor Company

Arlan J. Clayton
FloMet LLC

James R. Dale*
Metal Powder Industries Federation

Ron Dietrich
OMG Americas

Sara Dillich
U.S. Department of Energy

Robert B. Dixon
Crucible Research Center

Stephen Dunmead
OMG Americas

Harald H. Eifert
Innovationsstiftung Hamburg

William B. Eisen
Crucible Research Center

Thomas E. Friday
National Carbide Die Company

George P. Gasbarre, Jr.
Gasbarre Products, Inc.

Thomas Gasbarre*
Gasbarre Products, Inc.

Randall M. German
Center for Innovative Sintered Products

John C. Hebeisen
Bodycote IMT, Inc.

William B. Hirsch
Keystone Powdered Metal Company

William Hofmeister
Vanderbilt University

William F. Jandeska, Jr.*
GM Powertrain Group

Peter K. Jones
Stackpole Limited

Don Kupp*
Fraunhofer USA

Chaman Lall
Metal Powder Products Company

Robert Lander
Stackpole Limited

Alan Lawley*
Drexel University

Deepak S. Madan
F. W. Winter, Inc. & Co.

Stephen J. Mashl
Bodycote IMT, Inc.

Pat McGeehan*
Hoeganaes Corporation

William Michael
Hoeganaes Corporation

K. S. Narasimhan
Hoeganaes Corporation

Craig C. Paullin
Pacific Sintered Metals

Thomas W. Pelletiers
United States Bronze Powders, Inc.

Irene J. Petrick*
Center for Innovative Sintered Products

Stephen Ridder
National Institute of Standards and Technology

Prasan K. Samal
OMG Americas

Howard I. Sanderow*
Management & Engineering Technologies

John E. Smugeresky
Sandia National Laboratory

Mike Soboroff
U.S. Department of Energy

Hans Soderhjelm
Hoganas AB

Donald J. Spence, Jr.*
GKN Sinter Metals

Blaine A. Stebick
Windfall Products, Inc.

Thomas F. Stephenson
Inco Technical Services Limited

Terry N. Tiegs
Oak Ridge National Laboratory

Ted A. Tomlin
FloMet LLC

Yves Trudel
QMP

Jaak VandenSype
Praxair, Inc.

Manfred Weber
GKN Sinter Metals

Donald G. White*
Metal Powder Industries Federation

Donald T. Whychell, Sr.
CM Furnaces, Inc.

Leonard Wolberg*
Dorst America, Inc.

* Roadmapping Oversight Committee members

B Appendix: List of Acronyms

AGMA	American Gear Manufacturers Association
ASTM	American Society for Testing and Materials
ATP	Advanced Technology Program
CISP	Center for Innovative Sintered Products
CPMT	Center for Powder Metallurgy Technology
CTC	Concurrent Technologies Corporation
DOD	Department of Defense
DOE	Department of Energy
HIP	hot isostatic pressing
MIM	metal injection molding
MMCs	metal matrix composites
MPIF	Metal Powder Industries Federation
NASA	National Aeronautics and Space Administration
NDE	non-destructive evaluation
NIH	National Institute of Health
NIST	National Institute of Standards and Technology
NSF	National Science Foundation
OEM	original equipment manufacturers
PIM	powder injection molding
P/M	powder metallurgy (the process)
PM^2	powder metallurgy and particulate materials
PMRC	Powder Metallurgy Research Center
PTIA	Pennsylvania Technology Investment Authority